SYNOPSIS OF PROPOSED RESEARCH WORK

Titled

Theoretical Studies of Fiber Kerr Nonlinearity effect and its Various Applications.

For the degree of Doctor of Philosophy in Physics with permission from the Department of Physics, Faculty of Science, L. N. Mithila University, Darbhanga, 846008.

Submitted By

Mr. Subhash Chandra Prasad

Interview Roll no of Pat: E2215008

Under The supervision of

Dr. Sanjay Bhagat

Assistant Professor,
Department of Physics

S.B.S.S. College Begusarai, 851101.

(A Constituent unit of L.N.M.U. Darbhanga)

Forwarded
Irum
18/4/24

18.04.24

18.04.24

Prof. & Head
Dept. of Physics
L.N.M.U. Darbhanga

Dean
Faculty of Science
L.N.M.U. Darbhanga

Introduction:

The modern high capacity core communication network uses optical fibers to transmit Information from one point to another as modulated light pulses. The optical fiber is a dielectric cylindrical waveguide made up of low-cost material silica. The basic phenomenon responsible for guiding the light pulses inside the optical fiber is total internal reflection [1]. The uncladded optical fibers manufactured in the early 1920s Where it is not suitable for information transfer at long distances [1]. In the 1950s, the use of the cladding layer was a starting point for the field of fiber optics and led to a significant improvement in the fiber characteristics [1]. During the 1960s, the transmission of images through the glass fibers demonstrated the signifcant development of the field of fiber optics [1], [2]. The fibers manufactured during that time had a drawback of extreme power loss of >>>1000 dB/km while the optical light is transmitted. Further research efforts in the 1970s reduced the loss of the silica-based fibers below 20dB/km [1] During the late 1970s, advancements in fiber fabrication technology significantly reduced the fiber loss down to 0.2 dB/km in the 1550 nm wavelength range [1]. That eventually led to a breakthrough in the field of optical fiber communication systems [1]. During the1990s, the transmission of images through the glass fibers demonstrated the significant development of the field of fiber optics.The fibers manufactured during that time had a drawback of extreme power loss of >>> 1000 dB/km while the optical light is transmitted. Further research efforts in the 1970s reduced the loss of the silica-based fibers below 20 dB/km [1]. During the late 1970s, advancements in fiber fabrication technology significantly reduced the fiber loss down to 0.2 dB/km in the 1550 nm wavelength range [1]. That eventually led to a breakthrough in the field of optical fiber communication systems [1]. During the 1990s, the optical fibers were doped with rare-earth elements such as Erbium. That led to the development of the Erbium-doped fiber amplifiers (EDFAs) and fiber lasers [1],[3].The invention of EDFAS and cost-effective manufacturing of standard single-mode fibers (SSMFS) with less than 0.2 dB/km attenuation marked the beginning of commercially viable fiber-optic communication systems. Since the deployment, the optical communication systems underwent several technical evolutions to fulfil the requirements of high-speed communications. The emergence of bandwidth-hungry applications, such as cloud services and virtual reality, has fueled the global network traffic increase to a large extent [4-7]. Furthermore human-centered applications like video gaming and the exchange of multimedia content via smartphones are among the most bandwidth-consuming applications. That leads to a strong requirement for an increase in the access network capacity, and consequently, for the core optical network capacities to meet such ever-increasing traffic demands [7].The deployment of wavelength division multiplexing (WDM) technology, which enables the multiplexing of several optical signals in the same fiber, dramatically increases the fiber capacity [8],[9]. A few years ago, an optical super channel system has been introduced for 400 Gb/s or 1 Tb/s optical transmission systems [3]-[16]. This system effectively splits the given WDM channel into smaller subcarriers separated by smaller guard-bands an transmitted as a single entity along the optical network. The super channel technique has several benefits over the single-carrier systems [16]. It has

lower requirements in terms of optical signal-to-noise ratio (OSNR) and analog-to-digital converters/digital-to-analog converters bandwidth [16]. In comparison with single-carrier 400 Gb/s and 1 Tb/s transmission systems, the super channel systems exhibit better transmission performance. However, the transmission impairments in the optical fiber degrade the performance of the high data-rate optical super channel systems. For example, the chromatic dispersion (CD) introduces a frequency-dependent phase shift to the signals and acts as a primary limiting factor in provisioning a reliable long-haul optical communication link 17]. It is noteworthy that there are various optical and electrical techniques available to combat the adverse effect of the CD in a long-haul optical communication system[17]-[21].Another significant impairment that limits the transmission performance of the long-haul optical communication system is the fiber nonlinearity [7]. The nonlinearity effects in the optical fiber are due to an electro-optic effect, referred to as the Kerr effect,which arises from the dependence of the optical fiber refractive index on the transmit signal power[2], [7]. That makes the optical fiber channel different from other transmission media used for the information transfer. In a linear transmission medium, the information signals are usually perturbed by the additive noise, which generally results in channel capacities monotonically increasing with transmit power, thereby a corresponding increase in the SNR. However, the detrimental effects of Kerr-induced signal nonlinear distortions grow at a faster rate than the SNR capacity gain at higher launch powers. That in turn leads the channel capacity to be a non-monotonic function of the transmit launch power with a maximum value at a particular launch power termed as optimum launch power. The achievable transmission rate decreases rapidly beyond the optimal power point as the launch power increases due to the corresponding increase in the Kerr-induced signal nonlinear distortions[2].The transmission performance of the single-channel optical communication systems is mainly limited by the intra-channel Kerr nonlinearity effect. The intra-channel nonlinear interactions can be categorized into three types: (i) self-phase modulation (SPM), (ii) intra-channel cross-phase modulation XPM), and (iii) intra-channel four- wave mixing (IFWM). It is important to mention that the SPM, IXPM, and IFWM can be compensated well using digital nonlinearity compensation (NLC) techniques. In WDM superchannel systems, a significant portion of the nonlinear distortion comes from the nonlinear interaction between the channel under consideration and the co- propagating signals in adjacent channels, referred to as inter-channel nonlinearity effects [2]. The inter-channel nonlinear effects can be classified into three types: (i) XPM, (ii) cross-polarization modulation (XPolM), and (iii) FWM[22], [23]. In recent years, the spectral efficiency of the polarization division multiplexed (PDM) optical communication systems have dramatically improved by introducing a promising detection technique referred to as coherent detection. The coherent detection also enables the implementation of the advanced forward error-correction coding techniques and the adaptive digital signal processing (DSP) algorithms to combat time-varying transmission impairments 2 A plethora of NLC techniques based on DSP has been developed in the literature to deal with the Kerr nonlinearity effect.

In this research work, we provide a comprehensive description of the characteristics of the optical fiber channel, the theory behind the origin of the Kerr effect, the development of the pulse propagation equation, the numerical and analytical tools used for solving the pulse

propagation equation, and various Kerr-induced nonlinearity effects in the optical fiber channel. We also provide a concise review of various state-of-the-art DSP techniques available in the literature to deal with the detrimental effects of the Kerr-induced fiber nonlinearity effects. For the maximum benefit of the readers, we adopt a didactic approach with the help of a very detailed mathematical interpretation for various optical phenomenon, processes, models, and methods covered in this tutorial. Remainder of this tutorial is organized as follows. Section 2 explains the characteristics of the optical fiber channel.

Section 3 describes the nonlinear susceptibility and the Kerr effect. Section 4 provides the physics behind the pulse propagation in optical fiber. Section 5 demonstrates various mathematical tools

II THEORETICAL DEVELOPMENT AND MATHEMATICAL MODELING OF KERR EFFECT IN OPTICAL FIBER

II(1) LITERATURE REVIEW FOR THE PROPOSED RESEARCH WORK

The first nonlinear optical effect to be predicted was two-photon absorption, by Maria Goeppert Mayer for her PhD in 1931, but it remained an unexplored theoretical curiosity until 1961 and the almost simultaneous observation of two-photon absorption at Bell Labs[23] and the discovery of second-harmonic generation by Peter Franken et al. at University of Michigan, both shortly after the construction of the first laser by Theodore Maiman.[24] However, some nonlinear effects were discovered before the development of the laser.[25] The theoretical basis for many nonlinear processes were first described in Bloembergen's monograph "Nonlinear Optics".[26]The Kerr effect was discovered in 1875 by Scottish physicist John Kerr. Two special cases of the Kerr effect are normally considered, these being the Kerr electro-optic effect, or DC Kerr effect, and the optical Kerr effect, or AC Kerr effect. These two phenomenon are understand by the following mathematical explanation. When the electromagnetic waves are propagating through the core of the optical fiber then, the core of optical fiber may be get polarize and it is depending on its intensity of incident wave and dielectric of core materials. If the week incident electromagnetic wave propagating through the optical fiber then the dielectric polarization P can be relating with electric field E of the electromagnetic wave as:

$$P = \epsilon_0 \chi^1 E,$$

Where $\epsilon_0$permittivity of free is space and χ^1 is the first order susceptibility or linear susceptibility.Mechanism of this polarization phenomenon are understanding from the following fig.a and fig. b. Fig a representing charge model of an atom when electromagnetic wave is propagating and incident on an atom of core material then the components of electric field of the incident wave try to oscillate the charge model of atom according as the fig. b

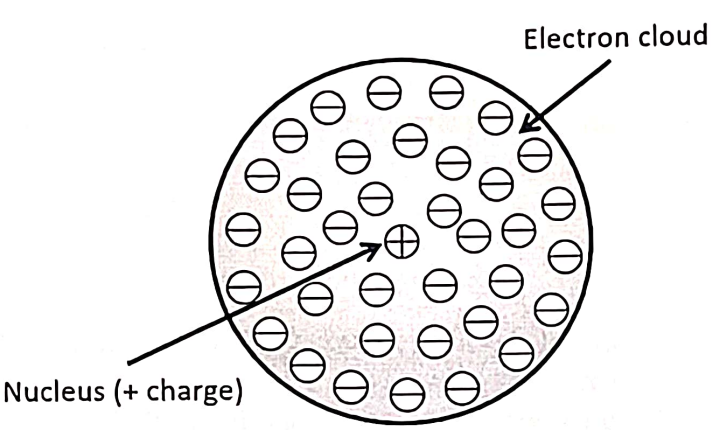

Fig. a

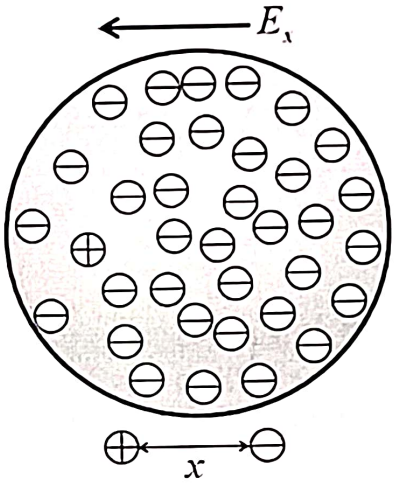

Fig. b

Here the centre of mass of positive and negative charges of atom is get displacement of x due to the incident electric field so, responsible external electric force is $E_x \cdot q_e$ and restoring force is –Kx due to the oscillating behaviour of charges .

Now according to the Newton's law of motion:

Net force= External Force + Force of restoration

$$m\frac{d^2x}{d^2t} = q_e \cdot E_x - Kx$$

$$\text{or } \frac{d^2x}{d^2t} + \omega_0^2 x = \frac{q_e}{m} E_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $\omega_0 = \sqrt{\frac{K}{m}}$ is the natural frequency of oscillation

Assume applied electric field $\boldsymbol{E_x = E_0 \exp^{(-j\omega t)}}$ ……(2)

The displacement x(t) due to the applied field also change harmonically in the steady state and try a solution as

$$x(t) = B.\exp^{(-j\omega t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Subsititing (3),and (2) in equation (1) we get

$$B = \frac{E_0 q_e}{m(\omega_0^2 - \omega^2)}$$

$$\text{And } x(t) = \frac{q_e}{m(\omega_0^2 - \omega^2)} E_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The dipole moment of an atom is given as

$$p = q_e x(t) = \frac{q_e^2}{m(\omega_0^2 - \omega^2)} E_x \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In general $p = q_e x(t) = \frac{q_e^2}{m(\omega_0^2 - \omega^2)} E$ .....(6)

If we define P = Np as the dielectric polarization, (6) can be written as:

$$P = \frac{Nq_e^2}{m(\omega_0^2 - \omega^2)} E$$

Where N is no of atoms per unit volume

Now If the incident electromagnetic field is intense, the relation between the restoration force and the displacement is nonlinear, and thereby, the electron cloud oscillation is not harmonic[27]. In this case, the relation between the dielectric polarization P and the electric dipoles are nonlinear, which can be generalized as [27]:

$P = \epsilon_0(\chi^1 E^1 + \chi^2 E^2 + \chi^3 E^3 ....)$.....(7)

The Kerr Effect

The nonlinearity effects in optical fiber originate from the third-order susceptibility χ^3. One of the primary sources of the nonlinearity effect in optical fiber is the χ^3induced nonlinear refraction, the Kerr effect, a phenomenon referring to the light intensity-dependent refractive index [27]. Assume that the electromagnetic field incident on the optical fiber core has only E_x and H_y components. Then, the tensor equation in (7) can be simplified for a centrally symmetric dielectric material
as [27]:

$P_x = \varepsilon_0 \chi^1_{xx} E_x + \varepsilon_0 \chi^3_{xxx} E_x^3$.....(8)

Under this effect a phenomenon reffering to the light intensity –dependent refractive index and many material reractive index can be describe by the relation [28]

$n = n_0 + n_2 \langle \hat{E}^2 \rangle$

Where n_0 represent the zero field or weak field refractive index and n_2 (sometimes called the second order index of refraction) gives the rate at which the refractive index increases with the optical intensity.

II(2) WORK PLAN AS PER OBJECTIVE AND METHODOLOGY

Pulse propagation in optical fibers

The wave propagation in dispersive nonlinear media is governed by the fundamental theory of electromagnetic wave propagation underpinned by the Maxwell's equations [1]. Using Maxwell's equations, one can easily show that:

$$\nabla \times \nabla \times E = -\frac{1}{c^2}\frac{d^2E}{dt^2} - \mu_0 \frac{\partial^2 P}{\partial t^2}$$ .....(9)

Where μ_0 is permeability of the free space.

For the Kerr effect-based nonlinearity in optical fiber, the induced dielectric polarization P(r,t) consists of two parts such as [1]:

$P(r,t) = P_L(r,t) + P_{NL}(r,t)$.....(10)

Where P_L and P_{NL} are the linear and nonlinear parts which are given as:

$$P_L(r,t) = \varepsilon_0 \int_{-\infty}^{\infty} \chi^{(1)}(t-t')E(r,t')dt'$$

And

$$P_{NL}(r,t) = \varepsilon_0 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \chi^{(3)}(t-t_1, t-t_2, t-t_3) : E(r,t_1)E(r,t_2)E(r,t_3)dt_1dt_2dt_3$$

Nonlinear Schrödinger equation

From equation (9) and (10), we can represent the wave equation as:

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_0 \frac{\partial^2 P_L}{\partial t^2} + \mu_0 \frac{\partial^2 P_{NL}}{\partial t^2}, \ldots\ldots\ldots\ldots(11)$$

To solve the wave equation in (11), we adopt several simplifying assumptions including [1]:

(a) The nonlinear part of the dielectric polarization P_{NL} is treated as a small perturbation to the linear part P_L;
(b) A scalar approach is adopted, i.e. the optical field is assumed to maintain the polarization along the length of the fiber; and
(c) A quasi-monochromatic assumption for the optical field.

Mathematical tools for solving the propagation equation

1. Numerical approximation method

2. Analytical approximation methods

COMPUTATIONAL SIMULATION THROUGH SCI LAB (OPEN SOURCE)

Scilab is a free and open-source, cross-platform numerical computational package and a higlevel, numerically oriented programming language. It can be used for signal processing, statistical analysis, image enhancement, fluid dynamics simulations, numerical optimization, and modeling, simulation of explicit and implicit dynamical systems and (if the corresponding toolbox is installed) symbolic manipulations. Scilab is one of the two major open-source alternatives to MATLAB, the other one being GNU Octave. Scilab puts less emphasis on syntactic compatibility with MATLAB than Octave does, but it is similar enough that some authors suggest that it is easy to transfer skills between the two systems. Scilab is a high-level, numerically oriented programming language. The language provides an interpreted programming environment, with matrices as the main data type. By using matrix-based computation, dynamic typing, and automatic memory management, many numerical problems may be expressed in a reduced number of. code lines, as compared to similar solutions may be using traditional languages, such as Fortran, C, or C++. This allows users to rapidly construct models for a range of mathematical problems. While the language provides simple matrix operations such as multiplication, the Scilab package also provides a library of high-level operations
such as correlation and complex multidimensional arithmetic. The software can be

used for signal processing, statistical analysis, image enhancement, fluid dynamics simulations, and numerical optimization. Scilab also includes a free package called Xcos (a fork of Scicos based on Modelica language) for modeling and simulation of explicit and implicit dynamical systems, including both continuous and discrete sub-systems. Xcos is the open source equivalent to Simulink from MathWorks. As the syntax of Scilab is similar to MATLAB, Scilab includes a source code translator for assisting the conversion of code from MATLAB to Scilab. Scilab is available free of cost under an open source license. Due to the open source nature of the software, some user contributions have been integrated into the main program.

Applications of Kerr effect:

It is found that many applications of Kerr effect have in picture some few are describe here, Optical signal processing at ultra-low powers in bottle microresonators using the Kerr effect.[29].,Direct Detection of Nonlinear Ferromagnetic Resonance in Thin Films by the Magneto-Optical Kerr Effect[30], High performance of an all-optical two-bit analog-to-digital converter based on Kerr effect nonlinear nanocavities[**31**], Information rates in Kerr nonlinearity limited optical fiber communication systems[**32**],and details wii describe in thesis.

REFERENCE:

[1]. Agrawal G P 1995 Nonlinear Fiber Optics (San Diego:Academic)

[2]. Agrawal G P 2000 *Nonlinear Fiber Optics* (Berlin: Springer)

[3]. Soma D *et al* 2018 *J. Lightwave Technol.* **36,** 1362

[4]. Chen M, Saad W Yin C and Debbah M 2019 *IEEE Trans.Commun.* **67,**4267
[5]. Zhang J, Rajendran S, Sun Z, Woods R and Hanzo L 2019 IEEE Wirel. Commun. 26,92
[6]. Restuccia F, D'Oro S, Melodia T and Hanzo L 2018 IEEE
Internet Things J. 5,4829
[7]. Amari A et al 2017 IEEE Commun. Surv. Tutorials 19,3097
[8]. Xu C, Liu X and Wei X 2004 *IEEE J. Sel. Top. Quantum Electron.* **10,**281
[9].*Laperle C, Villeneuve B, Zhang Z and McGhan D 2008 J. Lightwave Technol. 26, 168*
[10]. Sunish Kumar O S, Amari A, Dobre O A and Venkatesan R 2018 IEEE Photonics Technol. Lett. 30 769
[11]. Amari A et al 2020 IEEE Photonics Technol. Lett. 32 1435
[12]. Nguyen T T, Harper P, Sunish Kumar O S and Ellis A 2020Proc. Opt. Fiber Commun. Conf. Exhib. (San Diego: OSA)
[13]. Kumar O S S *et al* 2017 *Proc. Asia Commun. Photonics Conf.*

(Guangzhou: IEEE)
[14]. Rios-Müller R *et al* 2015 *J. Lightwave Technol.* 33 1402
[15]. Rios-Müller R *et al* 2015 *Proc. Eur. Conf. Opt. Commun.* (Spain: IEEE)
[16]. Chandrasekhar S and Liu X 2012 J. Lightwave Technol.30, 3816
[17]. Xia Z, Cui S, Ke C, Fu S, Tang M and Liu D 2016 Proc. Opt.Fiber Commun. Conf. Exhib. (Anaheim: OSA)
[18]. Killey R I, Watts P M, Mikhailov V, Glick M and Bayvel P 2005 IEEE Photonics Technol. Lett. 17, 714
[19]. Kuschnerov M et al 2009 J. Lightwave Technol. 27 3614
[20]. Renaudier J et al 2010 Bell Lab. Tech. J. 14 27
[21]. Savory S J 2006 Bell Lab. Tech. J. 42 407
[22]. Kumar O S S et al 2014 Proc. Int. Conf. Signal Process. Integr. Netw. (Noida: IEEE)
[23] Kaiser, W.; Garrett, C. G. B. (1961). "Two-Photon Excitation in CaF2:Eu2+". Physical Review Letters. 7 (6): 229. (1961)

[24] Rigamonti, Luca "Schiff base metal complexes for second order nonlinear optics" La Chimica & l'Industria (3): 118–122.(April 2010)

[25] Lewis, Gilbert N.; Lipkin, David; Magel, Theodore T. "Reversible Photochemical Processes in Rigid Media. A Study of the Phosphorescent State". Journal of the American Chemical Society. 63 (11): 3005–3018.(November 1941).

[26] Bloembergen, Nicolaas . Nonlinear Optics. World Scientific. ISBN 978-9810225995.(1965)

[27] Kumar S and Jamal M Fiber Optic Communications:Fundamentals and Applications (New Jersey: Wiley) 2014

[28] Boyd R. Nonlinear Optics. 3th ed. San Diego, CA: Academic Press; 2003.

[29] Michael P¨ollinger and Arno Rauschenbeutel optics express, vol 18 no 17 page 17764-17775,16 august 2010

[30].T. Gerrits, P. Krivosik, M. L. Schneider, C. E. Patton, and T. J. Silva, "Direct Detection of Nonlinear Ferromagnetic Resonance in Thin Films by the Magneto-Optical Kerr Effect," Phys. Rev. Lett., vol. 98, no. 20, p. 207602, May 2007, doi: 10.1103/PhysRevLett.98.207602.

[31] T. Xu, N. A. Shevchenko, Y. Zhang, C. Jin, J. Zhao, and T. Liu, "Information rates in Kerr nonlinearity limited optical fiber communication systems," Opt. Express, vol. 29, no. 11, p. 17428, May 2021, doi: 10.1364/OE.415753.

[32].G. Berrettini, G. Meloni, A. Bogoni, and L. Poti, "All-Optical 2$\,\times\,$2 Switch Based on Kerr Effect in Highly Nonlinear Fiber for Ultrafast Applications," *IEEE Photon. Technol. Lett.*, vol. 18, no. 23, pp. 2439–2441, Dec. 2006, doi: 10.1109/LPT.2006.881244.

Signature of Research Scholar with date: Subhash Chandra Prasad
13-04-204

Signature of Supervisor with date:

18.04.24

Signature of Head of the Department(With date and Seal)

Prof. & Head
Univ. Dept. of Phys.
L.N. Mithila University, Darbhanga